Observing and Modeling the Surface Scattering Layer of First-Year Arctic Sea Ice

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LONG-TERM GOALS

The long-term goal of this work is to increase the quantitative understanding of the partitioning of incident solar radiation by sea ice. The partitioning of shortwave radiation into components backscattered to the atmosphere, absorbed by the ice, and transmitted to the ocean is central to ice-albedo feedback, the mean annual cycle of ice thickness, mechanical and biological properties of the ice, and the qualitative and quantitative properties of light fields available to under-ice biological communities. This partitioning is known to depend strongly on the physical properties of the ice cover, including ice concentration, snow cover, area, depth and size of liquid water ponds, and the presence of surface scattering layers. The focus of this research is to address the impact of surface scattering layers on the partitioning of incident solar radiation at the atmosphere-sea ice-ocean interface.

OBJECTIVES

The objective of this work is to develop a conceptual model of how surface scattering layers on melting first-year sea ice govern the partitioning of incident shortwave radiation. This includes improving the physics employed in models that relate the physical and optical properties of sea ice.

To achieve this objective, we are conducting model simulations and field observations of surface scattering. Observations focus on (i) how surface scattering layers evolve, and (ii) how the physical properties of these layers are related to their inherent optical properties (IOPs). Modeling efforts focus on diagnosing relationships between the structural and optical properties of these layers which are typically drained and have low density and coarse grains. Results will be used to improve parameterizations of the surface energy and mass balances of sea ice during summer and will treat both bare and ponded ice.

APPROACH

Our approach to this effort during Year 1 has involved two activities: (i) implementation of a structural-optical model (*Light et al.*, 2003a; *Light et al.*, in preparation) along with a two-dimensional

Monte Carlo radiative transfer model (2DMCRT) (*Light et al.*, 2003b) to simulate existing spectral albedo data acquired in the presence of surface scattering layers, and (ii) design of a simple device that enables the collection of optical property data on surface scattering layers sampled directly from melting sea ice covers.

A framework for the modeling component is illustrated in Figure 1. Direct observations of physical properties, including temperature (T), salinity (S), ice density (ρ), microstructure (e.g., effective grain sizes for snow grains or melting ice crystals, size and number distributions of gas and brine inclusions), along with information about any light absorbing impurities included within the ice (e.g., dust, soot, suspended particulate material) are input to a structural-optical model. The structural-optical model uses these physical property data to predict IOPs for the ice cover. The principal IOPs are spectral absorption coefficient (κ_λ), scattering coefficient, (σ), and scattering phase function ($p[\theta]$). Structural-optical models are still nascent and the parameterizations on which they rely are still being developed and tested (e.g., *Light et al.*, in preparation).

Boundary conditions for the radiative transfer problem (e.g., domain geometry and characteristics of the incident light field) are then used, along with calculated IOPs, as input to a radiative transfer model for the calculation of apparent optical properties (AOPs) which include spectral albedo (α_λ), spectral transmittance (T_λ), and spectral radiance and irradiance distributions (e.g., $F_\lambda[z]$). The latter quantities depend on depth z in the ice.

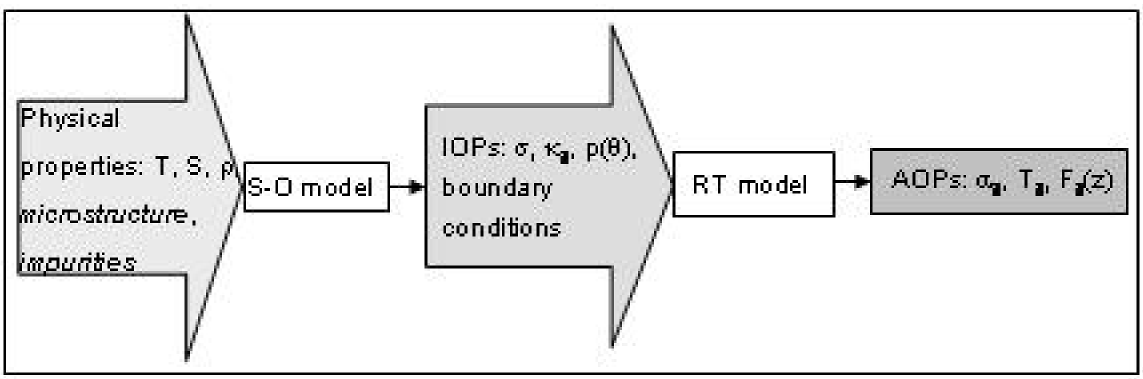

Figure 1. Schematic illustrating how structural-optical models use physical properties to predict inherent optical properties (IOPs), and then how radiative transfer models use these IOPs, along with boundary conditions to predict apparent optical properties (AOPs).

Our approach to modeling observed α_λ data is based on this framework, with two significant additions. We use the comparison of predicted and observed AOPs to modify estimates of the details of the ice microstructure that can only be crudely estimated from direct measurements, and we use this comparison to improve the parameterizations employed by the structural-optical model. Results from this work are discussed below.

The key to developing our existing structural-optical model was the acquisition of simultaneously obtained structural and optical data (*Light*, 2000), and we think this is the best approach for studying the surface scattering layer. In previous studies, core samples were shipped from the field to a laboratory cold room. However, the surface layers of melting ice become porous and fragile over time, and it is therefore not practical to expect to transport or store samples from the uppermost portions of melting sea ice. To alleviate this problem, we are constructing an ‘optical core jacket’ that will enable us to sample the scattering properties of the surface layers on location. This jacket consists of a specialized core barrel coupled with optical sensors for measuring the amount of light transmitted through a core sample. Our approach to the design of this device includes performing radiative transfer model simulations of the ice types we anticipate sampling in order to specify the material and functional properties of the device. After construction and testing are complete, experiments using the jacket will be conducted on sea ice at Pt. Barrow, Alaska. Analysis of the resulting data will provide a basis for improving the structural-optical model, and applying the results to a variety of sea ice models.

Measurements made with the core jacket will use a bootstrap approach. Once a core is sampled from the ice, it will be placed within the jacket barrel. Coupled optical detectors will be used to measure T_λ for ambient diffuse incident radiation through the core. The top section of the segmented barrel will be removed (approximately 1 – 2 cm), the ice carefully sawed off, and another T_λ measurement made. This procedure of removing segments of the ice core and making sequential T_λ measurements will produce a data set detailing the vertical structure of optical properties within the surface scattering layers and throughout the core. The optical measurements will be conducted in concert with detailed physical property assessments of the various layers.

WORK COMPLETED

During Year 1 of this project we have (i) conducted modeling studies of existing α_λ data for ice with documented surface scattering layers, (ii) performed comprehensive model simulations of the optical core jacket, and (iii) designed the core jacket in preparation for its construction.

RESULTS

Modeling α_λ data

To better understand the physical and optical characteristics of surface scattering layers, we modeled α_λ data collected at the surface during routine measurements made by the ice physics program (see *Perovich et al*., 2002) at Ice Station SHEBA in the central Beaufort Sea. The analysis for multiyear ice was performed on data recorded at seven different locations on seven different days during the course of the summer melt season (Figure 2). The documented physical property characterizations were input to the structural-optical model, including the presence, layer thickness, and grain size of any snow at the surface, and crude estimates of melting ice grain size as a function of depth within the ice. Predicted IOPs were then input to the 2DMCRT model to solve the radiative transfer equation for a plane-parallel geometry with the observed ice thickness and incident light conditions. In each case, the comparison between observed and predicted α_λ was used to adjust the vertical profile of ice grain size within the surface layers. This adjustment of grain size is necessary because we do not have measurements of the statistics of the randomly shaped, distinctly non-spherical melting grains that comprise real sea ice, and even with such statistics, models for translating them into equivalent optical spherical grain sizes for use by the radiative transfer model are still under development.

Figure 2 shows that once the grain size profiles are adjusted, predicted α_λ values agree very closely with the observations. This is not surprising, given that the model is used to adjust the grain size profiles. Furthermore, our calculations indicate that the details of the vertical structure of the surface scattering layers have strong impact on α_λ. It is can also be seen that α_λ for the melting multiyear ice remains relatively constant over the course of the summer (with peak α_λ values between 0.74 and

0.88), despite an average total surface ablation of 60 – 70 cm. This, along with direct observations of the ice appearance, suggests the general persistence of surface scattering layers on summer sea ice, a property that will be a focal point of our investigation.

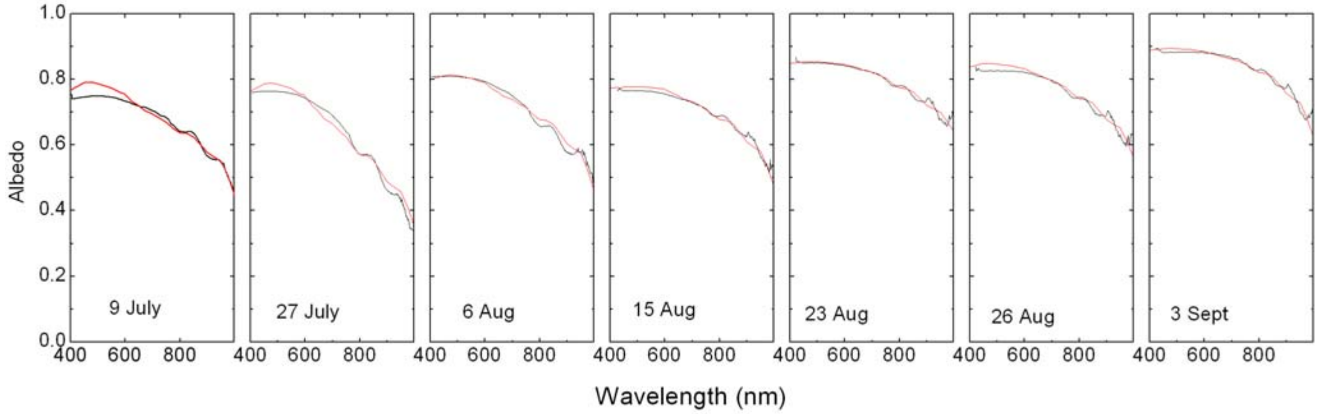

Figure 2. Observed and modeled spectral albedo for seven days during the SHEBA melt season.

Figure 3 shows vertical scattering coefficient profiles used for each of the seven cases shown in Fig. 2. To model each of these cases, four or five vertically stacked layers were used; each with uniform IOPs. To compare σ values associated with scatterers with different phase functions, each value of σ was adjusted to correspond to an asymmetry parameter of $g = 0.94$ via a similarity argument. Similarity arguments permit the comparison of inherent optical properties by adjusting the relative values of asymmetry parameter and scattering coefficient to represent the total attenuation due to scattering (*van de Hulst*, 1980; *Light et al*., 2003b).

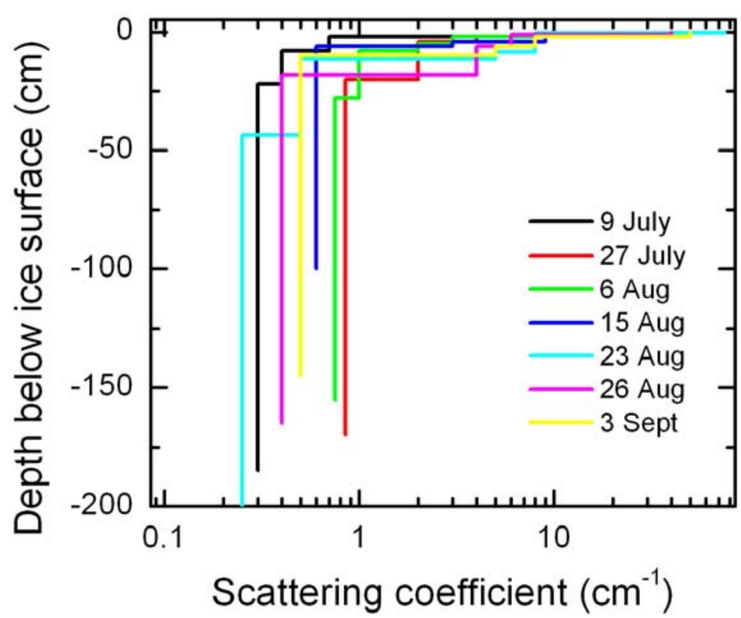

Figure 3. Plot of representative scattering coefficients as a function of depth in the ice for the seven cases shown in Fig. 2.

There is considerable variability in the σ values at all depths. For any one day, however, values show approximately two orders of magnitude variation over the uppermost 30 -50 cm. Because of these extremely large variations in scattering, this model analysis suggests that the surface scattering layers likely play a significant role in determining spectral albedo, absorption, and transmittance of bare, melting sea ice. This calculation provides a benchmark for predicting the optical properties of bare ice that will be studied during the field experiment. These determinations were made from multiyear ice and the focus of the field study will be on first-year ice, and the extent to which these determinations are unique and similar will be studied.

Optical core jacket

The 2DMCRT model has been used extensively to aid in the design of the core jacket. By establishing benchmark cases from the analysis presented in Figs. 2 and 3, it is possible to simulate radiative transfer in cores with optical properties similar to those we expect to study. The primary objective of the jacket design is to maximize the discrimination of IOPs through the length of a core sample, and from one core sample to the next.

Some of the basic questions that have been addressed include: (i) over what range of scattering coefficients should we anticipate making measurements? (ii) what barrel dimensions and segmentation lengths should be designed? (iii) what barrel interior optical properties will yield the most useful measurements? should the lining be highly reflecting or largely absorbing? diffuse or specular? (iv) what is the optimal geometry and position for the optical detectors?

To illustrate this design process, we summarize the tests addressing question (iii): the sensitivity of the inferred IOPs to small changes in the optical properties of the jacket lining. To carry out this test, we modeled the transport of a diffuse radiation field incident on the top surface of a core sample with spatially uniform scattering coefficient and phase function. The core sample was modeled with 0.1 cm clearance (air gap) between its circumference and the jacket lining. We tested our ability to discriminate small changes in IOP values depending on whether the jacket lining had a reflectivity of approximately 1 or approximately 0. The results indicate that for a given measured transmittance, the uncertainty in inferred scattering coefficient is much smaller when the reflectivity of the wall lining is 0.05 ± 0.05, than when it is 0.95 ± 0.05. This result indicates that we will more accurately identify appropriate values of σ if the device has absorbing interior walls, relative to one with highly reflecting walls. As a result of this calculation, our device design provides for a core barrel with black interior. As a result of additional calculations, the core barrel will be designed with a 10 cm interior radius (to accommodate standard 9 cm radius cores with an air gap), and segment lengths will vary from 1-2 cm for the surface layers to 15 cm for the interior portions of the core.

IMPACT/**APPLICATIONS**

A conceptual framework for describing structural-optical relationships in melting first-year sea ice will be developed based on the integrated optical and structural data sets. This framework will serve as a tool for predicting how the partitioning of shortwave radiation responds to physical changes in the surface layers of a melting ice cover. This is particularly important in modeling surface melt rates, the mean annual cycle of ice thickness, ice mechanical properties, solar heating of the upper ocean, and biological processes within the summer Arctic ice cover.

By direct observation of the physical processes that relate the ice structure to its optical properties, our understanding of the complex interactions between shortwave radiation and a melting ice cover can progress from qualitative to quantitative. First-year ice now dominates the coastal margins of the Arctic, and it may potentially cover much of the basin in a warmer Arctic, where its survival through the summer melt season will likely be tightly tied to the formation and persistence of surface scattering layers. Improved understanding of these fundamental physical processes will enable us to better understand the seasonality of a warmer Arctic, support improved operational models of the Arctic ice cover, enhance our ability to remotely monitor the state of the ice cover, and advance our capability to predict the partitioning of shortwave radiation by sea ice. The implications of these results for prediction and feedback processes will be explored in collaboration with Moritz and C. M. Bitz's ongoing studies utilizing a single column model of the ocean-ice-atmosphere system.

TRANSITIONS

We anticipate that results of this study will be incorporated into a revised parameterization of sea ice thermodynamics and this parameterization will then be incorporated into climate models (such as the Community Climate System Model, CCSM) and operational models (such as PIPS).

RELATED PROJECTS

An ongoing related project is "Studies of Arctic Climate Feedbacks Using SHEBA data and the NCAR Climate System Model" (NSF OPP-0084287), wherein Moritz and Bitz are using the Single Column Model version of CCSM to simulate the SHEBA year and to improve parameterizations within the CCSM.

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